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Evaluation of bending fatigue strength in automotive gear steel subjected to shot peening techniques.

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Abstract

The effect of residual stress is known to have a large influence on the integrity of engineered components including gears. Shot peening is a popular process used to introduce compressive residual stresses into a material which are beneficial to their fatigue life. Bending fatigue failure of gears is one of a number of failure modes a gear designer must account for and which can cause catastrophic failure of a gearbox.

This paper presents results from the Innovate UK funded ULTRAN project to demonstrate the effects of a number of different shot peening processes upon the bending fatigue strength of an automotive gear steel. Results to be presented include residual stress measurements, bending fatigue results from pulsator tested gears and a study of the fatigue crack growth in the material.

Four different shot peening techniques are presented along with baseline data. Whilst there was a large change in bending fatigue strength between the as-carburised and shot peened samples, the changes in residual stress caused by the optimised and the duplex shot peening methods did not correspond to a similarly dramatic increase in fatigue strength.

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Keywords: Gears; bending fatigue; residual stress; shot peening; fracture.

1. Introduction

The design of gears is often particularly focused on reducing failures due to fatigue processes. The gear designer has control over a number of material and geometrical factors which can be used to improve fatigue life. With the increasing importance of vehicle efficiency and tighter controls on emissions, there is a significant drive within the automotive industry to improve gearbox design and allow increases in efficiency and reductions in weight. To this

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end, an improvement in bending fatigue strength allows a reduction in tooth module and gear size, reducing weight and the sliding velocities encountered during tooth meshing.

Bending fatigue failure of gears occurs as a result of bending stresses in the tooth root when under load and can cause catastrophic damage to a gearbox due to tooth detachment. Research has shown that the majority of these failures have initiation sites located at or near the surface (Evans and Shaw 1996). The use of techniques to improve the near-surface properties of gears are therefore of great importance.

Shot peening is a controlled surface treatment process used to impart compressive residual stresses into the surface of a part and has been common practice for a range of automotive components for some time (Burrell 1985).

BS ISO 6336-5:2016 provides the gear designer with recommendations on the increase in bending fatigue strength for carburised and shot peened gear steels which range from 0-10% depending on the steel quality grade ML-MQ.

2. Experimental Methods

2.1. Sample Manufacture & Characterisation

Test gears were manufactured from forged 20MnCr5 blanks to the specifications provided in Table 1. The material was chosen to be representative of those commonly used in the automotive industry. The gears were subsequently heat treated using a commercial gear carburising process to achieve a surface hardness of 653-746Hv and a case depth of 0.8-1.0mm at 550Hv.

Table 1. Test gear specification

Module (*mm*)	3.9	Base circle diameter (*mm*)	106.2792
ISO 1328 Quality	6	Reference diameter (*mm*)	113.10
Number of teeth	29	Tip diameter (*mm*)	120.90
Face width (*mm*)	20	Root diameter (*mm*)	102.18

Four shot peening surface treatments were selected for testing in addition to an as-carburised baseline. Three processes were chosen from a commercial surface treatment supplier. The first process was selected from a standard range of treatments (S230H). The second process was an optimised single-stage process (S330H) whilst the third was an optimised two-stage (duplex) process (S330H+S110H). The process details for the three commercial processes are given in Table 2. The fourth treatment selected was an existing proprietary process using conditioned cut wire shot (CCW) comparable to the first three treatments. The process was selected to be representative of a typical process from the automotive industry and to investigate the advantages of the increased control over the distribution of shot size and hardness given by the CCW shot.

Table 2: Commercial shot peening process parameters.

Process	Peening intensity (*A*)	Coverage (*%*)
S230H	10-14	125
S330H	14-18	125
S330H + S110H	14-18, 3-6	125, 150

Near-surface residual stress levels for the baseline and each of the four shot peening processes were characterised using the X-ray diffraction technique (Society of Automotive Engineers 1980) and were carried out using a Stresstech Xstress 3000 G2R diffractometer fitted with a Cr-Kα X-ray tube. A combination of acid etching and electro-polishing was used for localised material removal at depths of 0.01, 0.02, 0.03, 0.04, 0.06, 0.10 and 0.15mm measured using a dial gauge. Residual stress measurements were taken in both profile and lead directions.

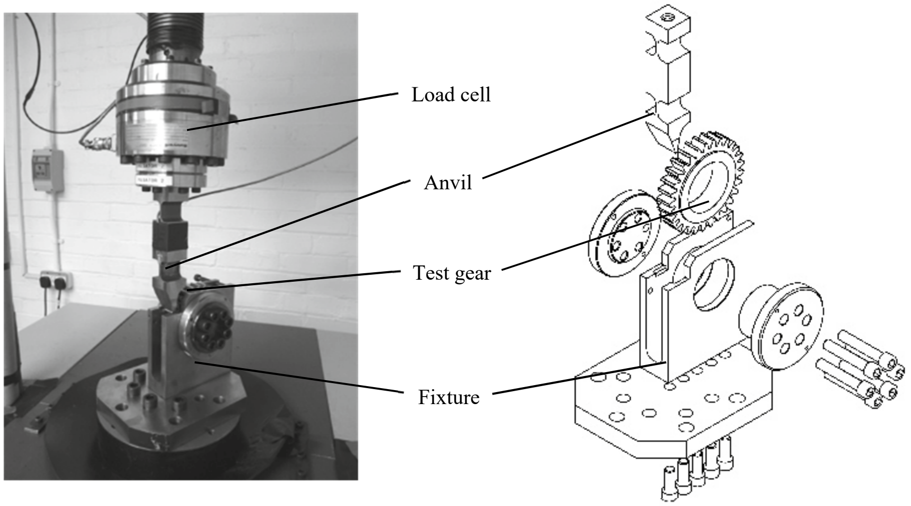

Figure 1: Pulsator testing setup.

2.2. Bending Fatigue Testing

The fatigue strength of the gears after surface treatment was characterised using a pulsator test method on an Instron 1603 resonance fatigue machine operating at approximately 150Hz. The gears were rigidly clamped into a bespoke test fixture which ensured that the load was projected through the base circle. The test setup is shown in Figure 1.

The load was applied using a flat self-aligning anvil and testing was completed using a staircase test model in accordance with BS ISO 12107:2003. A static preload of 55% of the dynamic load range with the load cycled between approximately 5% and 105% was used to establish an R ratio of 0.05.

The criteria for an endurance limit is based on 10^7 cycles. The ISO 12107 method defines the mean bending fatigue strength based on a 50% probability of failure. The 1% probability of failure was calculated by subtracting 2.33x the standard deviation for the test. After failure, the fracture surfaces were examined and initiation sites determined using a scanning electron microscope equipped with Energy-Dispersive X-ray spectroscopy (EDX) for chemical identification.

3. Results and Discussion

3.1. Residual Stress

The results for the average residual stress of the various gear sets are shown in Figure 2. The results show a significant variation in the maximum residual compressive stress between the baseline sample and all of the shot peened groups. The minimum increase in compressive residual stress was 760MPa. There are less significant differences between the different shot peening processes.

The CCW process produced the greatest effect with a maximum residual compressive stress of ~1GPa at a depth of ~0.01-0.03mm. The S230H process produced a maximum of ~900MPa at a depth of ~0.015mm. The S330H process produced a maximum comparable to the S230H process at a depth of ~0.03mm. The additional S110H stage of the duplex process appeared to have little effect upon the residual stress; overall the S330H+S110H duplex method produced lowest maximum residual compressive stress of 760MPa at a depth of ~0.02mm.

Typically the second stage of a duplex process would modify the residual stress profile and produce compressive residual stresses closer to the surface than the primary process, thus broadening the compressive residual stress peak. However in this instance the S110H stage did not have the desired effect. It is expected that the results presented are due to process control and this will be discussed with the fatigue testing results.

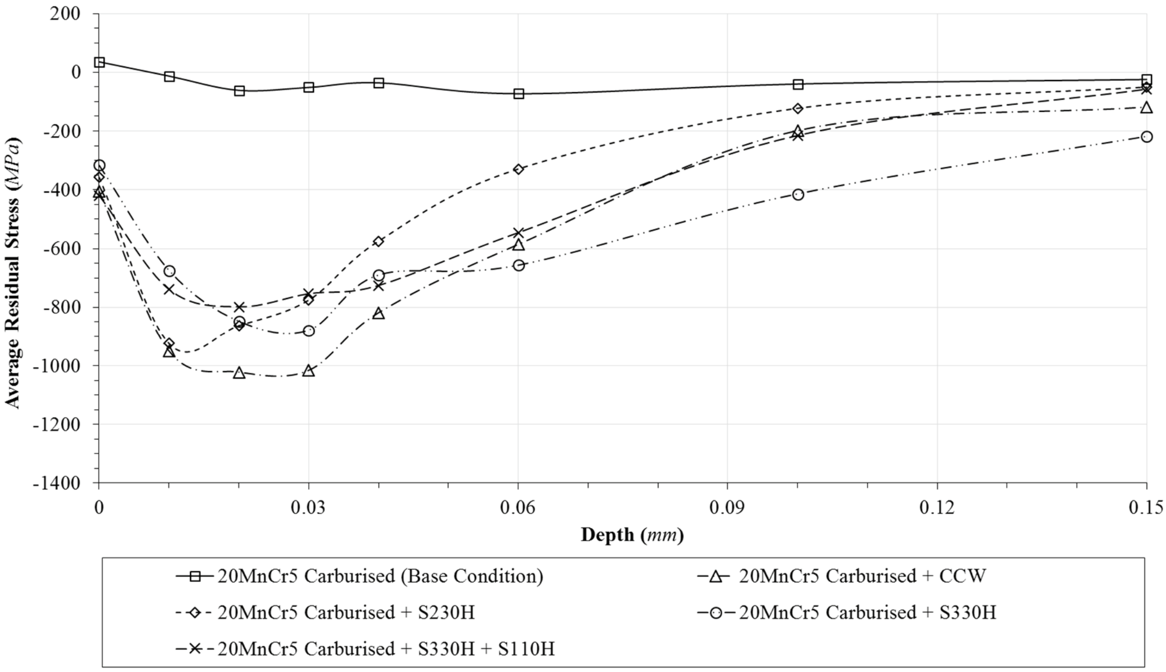

Figure 2: Residual stress profiles after different surface treatments.

3.2. Bending Fatigue Life

The results of the fatigue testing showed an improvement in fatigue life for all shot peened samples when compared to the baseline test with a minimum increase in fatigue strength of 61%. The results of the fatigue testing are given in Table 3 and Figure 3. Comparing values for the bending fatigue strength for 50% probability of failure, the CCW process provided an uplift of 86% over the baseline steel. The S230H, S330H and S330H+S110H processes provided increases of 61%, 64% and 66% respectively. The slight increase in bending fatigue strength for the S330H+S110H process suggests that the assumption made about process control due to the lower compressive residual stress is valid; had the compressive residual stress been consistently higher it would be expected to see this reflected in the fatigue performance.

Table 3: Bending fatigue test results.

Shot peening process	Mean bending fatigue strength (*MPa*)		Standard deviation (*MPa*)
	50% probability of failure	1% probability of failure	
None (baseline)	795	357	188
CCW	1475	1324	65
S230H	1281	1092	81
S330H	1306	1208	42
S330H + S110H	1317	1177	60

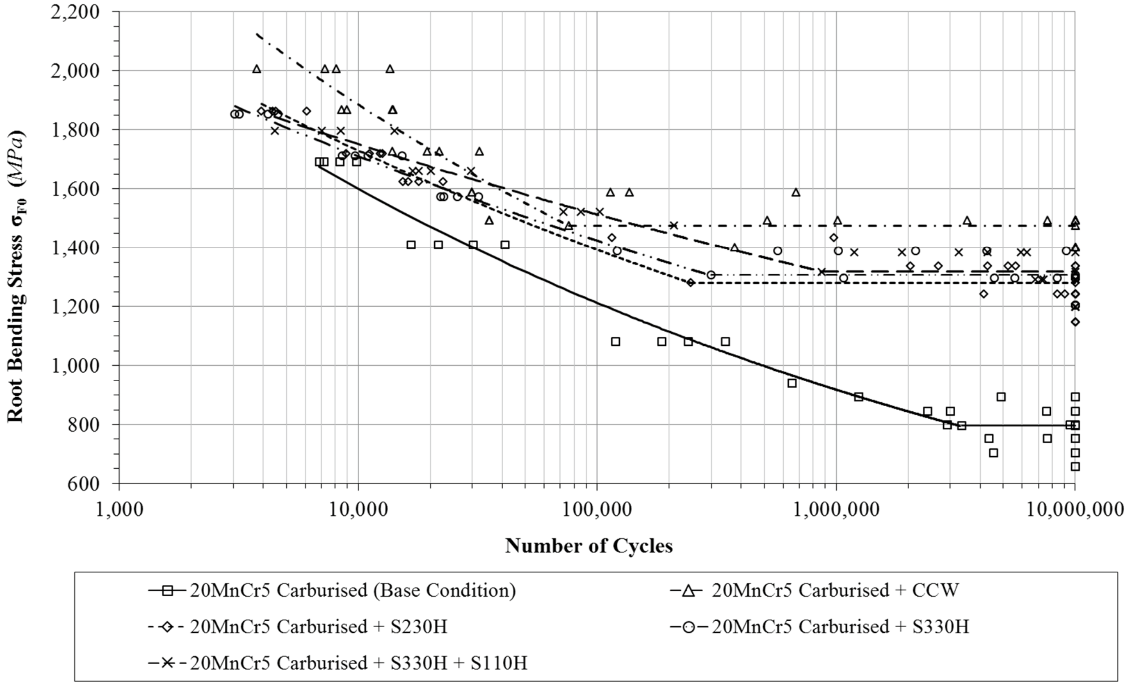

Figure 3: S-N curve of bending fatigue test results.

The standard deviation for each of the tests shows that there was a much more significant variance in results for the baseline test result, suggesting that the variability in compressive residual stress is much greater for the untreated steel; any shot peening process provides a more consistent residual stress even accounting for some process variability. Due to the high standard deviation of the baseline testing, it is otherwise not possible to reliably compare the bending fatigue strength for 1% probability of failure.

3.3. Fractography

The fracture faces for the baseline, CCW, S330H and S330H+S110H batches are shown in Figure 4. Inspection of the fracture faces after failure showed that the baseline test consistently failed due to surface-initiated cracking and this is consistent with previous findings where failure is initiated from within the intergranular oxidation caused by the gas carburising process.

It was found that for the S230H, S330H and S330H+S110H processes, failure resulted from sub-surface initiated cracks. Close inspection of the nucleation site for the sub-surface initiated samples indicated that failure was due to subsurface inclusions; for the S230H sample shown this was identified using EDX as rich in Manganese and Sulphur whilst the S330H failure shown was found to be rich in Aluminium, Oxygen, Calcium, Sulphur and Magnesium. This is consistent with previous results where the compressive residual stress imparted by the shot peening process works to suppress the weakness due to the intergranular oxidation and the inclusions in the gear steel caused by the steelmaking process become the next weakest link.

It was found that the CCW processed sample also failed entirely due to surface-initiated cracking, and this was not the expected result. Typically as with the other shot peened samples initiation would be driven to sub-surface contaminants. It should be noted that during manufacture two batches of steel castings were provided and that the first cast was used to produce both the baseline and CCW processes gear samples.

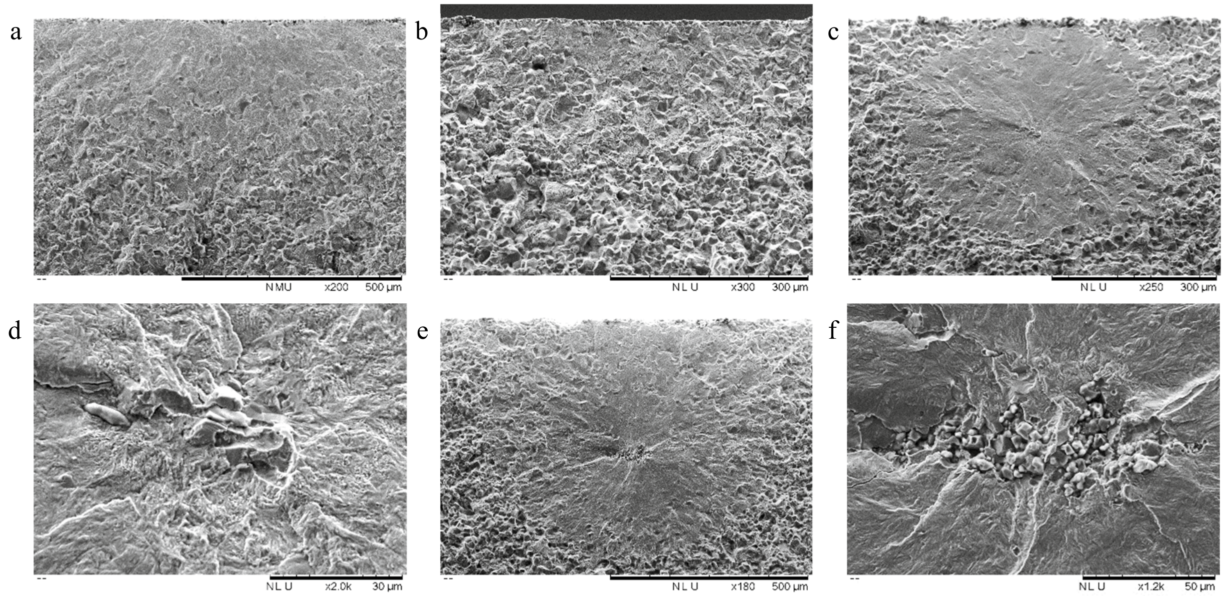

Figure 4: Fracture surfaces (a) Carburised (baseline) (b) Carburised + CCW (c) Carburised + S230H (d) Inclusion from Carburised + S220H sample (e) Carburised +S330H (f) Inclusion from Carburised + S330H sample

4. Conclusions and future work

The work presented in this paper shows that large increases in bending fatigue strength can be produced through additional surface preparation processes and that these increases greatly exceed the suggestions given in the relevant standards. The authors do note however that the nominal and allowable stress numbers shown in ISO 6336-5 for carburised steels were derived from gears that were subjected to post heat treatment cleaning processes such as shot blasting which will give an uplift in bending fatigue performance (see ISO 6336-5 section 6.6).

It was shown that the greatest increase in bending fatigue performance was given by the CCW process and that this also gave the most significant increase in compressive residual stress. From this, it is suggested that the improvement in the control of shot size and hardness can provide more a more stable and predictable residual stress profile. It is certainly clear that there is a positive relationship between compressive residual stress and bending fatigue life.

The work here investigated only a single CCW method and therefore there is scope for further work to investigate optimization of the CCW process through shot peening parameter control and the addition of additional secondary stages. Additional cut wire processes such as double conditioned cut wire (DCCW) and spherically conditioned cut wire (SCCW) may also be of interest.

Acknowledgements

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